

© Copyright 2018

Jeremy Albert

User-Centric Classification of Virtual Reality Locomotion Methods

Jeremy Albert

A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Science in Computer Science & Software Engineering

University of Washington

2018

Reading Committee:

Kelvin Sung, Chair

Yusuf Pisan

Arnold Lund

Program Authorized to Offer Degree:

Computing and Software System

University of Washington

Abstract

User-Centric Classification of Virtual Reality Locomotion Methods

Jeremy Albert

Chair of the Supervisory Committee:
Professor Kelvin Sung
Computing and Software System

The recent introduction of consumer grade virtual reality (VR) systems caused a renewed interest in the technology. However, virtual reality locomotion (VRL) remains a significant issue for virtual reality. VRL is traveling in an infinite-scale virtual world, while remaining in the confines of a room-scale real world. VRL remains an issue because of three fundamental challenges, sickness, presence, and fatigue. Sickness occurs when there is a conflict between a user's vestibular and visual senses; Presence occurs when a user feels they are truly in the virtual world; Fatigue occurs when a user expends muscular energy for a sustained period.

This thesis proposes the User-Centric Classification (UCC) framework for discussing, comparing, and identifying characteristics of VRL methods. The UCC framework classifies VRL methods according to three metrics, sickness, presence, and fatigue, where each metric is determined by how well a VRL method addresses the corresponding challenge. Results from previous VRL research, were analyzed in the UCC framework. Analysis indicated current

methods were designed to deliver performance in one of the challenges by sacrificing performance in the other two.

To test the validity and strengths of the UCC framework, we implemented the VRL methods of controller, teleport, and walking in a common testbed. We designed the testbed to expose the user to the three VRL challenges and developed a set of questionnaires to capture the user experience. Test results from 30 users showed that the three VRL methods produce different UCC metrics and that we can capture these differences. Contrasting the three methods with respect to the three VRL challenges allows us to discuss and compare methods in a meaningful way and to examine UCC metric trade-offs while searching for an ideal VRL method.

Contents

- Abstract 1
- Contents 3
- Chapter 1 Introduction 5
 - 1.1 VR Locomotion Unsolved 6
 - 1.2 Our Work 7
- Chapter 2 Literature Review 8
 - 2.1 VRL Challenges 8
 - 2.1.1 Sickness..... 8
 - 2.1.2 Presence 9
 - 2.1.3 Fatigue..... 11
 - 2.2 VRL Classification..... 12
 - 2.2.1 Previous Classifications 12
 - 2.2.2 Strengths and Limitations 13
- Chapter 3 User-Centric Classification 14
 - 3.1 Proposed Framework 14
 - 3.2 Existing VRL Methods 16
 - 3.3 Framework Analysis 17
- Chapter 4 The Testbed 19
 - 4.1 Testbed Implementation..... 19
 - 4.2 VRL Method Implementation..... 21
- Chapter 5 VRL Method Assessment..... 26
 - 5.1 Metric Questionnaires 26
 - 5.2 Testing Protocol 28
 - 5.3 User Testing 28
- Chapter 6 Results 31
 - 6.1 Questionnaire Results 31
 - 6.1.1 Data Summary 32
 - 6.1.2 Data Analysis 33
 - 6.1.3 UCC Assessment 35
 - 6.2 Ranking Results 36

6.2.1 Data Summary	37
6.2.2 Data Analysis	38
6.2.3 UCC Assessment	40
6.3 Discussion	40
Chapter 7 Conclusion.....	42
7.1 Contributions.....	42
7.2 Future work.....	43
References.....	44
Appendix A: Assets Used	47
Appendix B: Questions Asked.....	48
Appendix C: Data Collected	49

Chapter 1 Introduction

Broadly defined, virtual reality (VR) is a “realistic and immersive simulation of a three-dimensional environment, created using interactive software and hardware, and experienced or controlled by movement of the body [1].” This definition can include a large range of systems and applications. This paper will specifically focus on VR which uses a motion-tracked head-mounted display (HMD). HMDs consist of two displays that cover a user’s eyes and provide a stereoscopic illusion of depth. Tracking the motion of the HMD allows users to control the display by moving their head in the six degrees of freedom.

Developed in 1968, the first VR HMD is generally considered to be Ivan Sutherland’s “ultimate display”. This primitive system consisted of wire-frame graphics and a heavy HMD suspended from the ceiling. In 1985, Jaron Lanier coined the term virtual reality and founded VPL research, the first company to commercially offer a VR HMD. The early 1990’s saw a VR craze, as companies attempted to create VR systems at an affordable price, but technological restraints resulted in systems that were too costly or produced unsatisfactory VR experiences. As a result, public interest in VR waned over the following decade, until the Oculus Rift and HTC Vive were released in 2016. These current VR systems use infrared pulses to accurately track the user’s real-world movements, but they are still limited by the physical environment of the user.

Virtual reality locomotion (VRL) enables the user to move in an infinite-scale virtual-world, while staying confined in a room-scale real-world environment. When the virtual environment is the same size as the physical environment of the user, real-world locomotion can directly control the virtual-world locomotion. However, when the virtual environment is larger than the physical environment, an alternative locomotion method must be used. However, due to

the existence of fundamental challenges, finding an ideal VRL method is still an unsolved problem.

1.1 VR Locomotion Unsolved

Developers and researchers have identified and implemented many VRL methods, but there is no consensus for best way for a user to move in a virtual space [2]. Finding the best VRL method remains a significant issue because of three fundamental challenges, sickness, presence, and fatigue.

Some VR users can experience a type of motion sickness called VR sickness, which is believed to be caused by a sensory conflict. The awareness of the position of one's body, is determined by visual and non-visual senses, such as the vestibular system. When these senses are mis-matched, users can experience feelings similar to motion sickness. Some level of this incongruent sensory input will occur when moving in a virtual environment that is larger than the room-scale environment of the user.

Immersion is the amount that a VR application can create the sense of presence, which means that within the virtual world the user has a sense of “being there”. To alleviate VR sickness, some VRL methods reduce the amount of immersion in the VR application, thereby reducing the presence felt by the user. This reduced presence allows the user to focus on the non-visual signals more than the visual ones, alleviating sensory conflict.

Conversely, some VRL methods reduce sensory conflict by incorporating physical motion. Making VRL dependent on real-world motion allows the non-visual sensation of a user to match the visual sensation. These methods do not reduce the presence felt by a user, but this

leads to a physical ergonomics problem because VRL methods that require a large amounts of energy expenditure can lead to fatigue of the user.

1.2 Our Work

We propose a user-centric classification (UCC) framework of VRL methods based on how well the method solves the VRL challenges. In the UCC framework, sickness, presence, and fatigue, are metrics which describe and classify dissimilar VRL methods. This framework provides a common language of comparison that is technologically independent.

Furthermore, this classification can aid in the efforts to discover an ideal VRL solution. We believe the lack of a common locomotion method is a factor in limiting the main stream adoption of VR. Finding an ideal and common VRL solution would give VR users consistent experiences across applications and would allow developers to know how users are going to interact with their application.

We conducted an experiment that would tested several VRL methods within the UCC framework and provided insight on possible trade-offs between the metrics. The experiment was carried out in a custom designed and implemented a common testbed comparing VRL methods of controller, teleportation, and walking in place. Volunteers were enlisted to use each of those methods in the testbed. After testing, users were questioned about their experiences with each VRL method, as well as how each method compared to each other. We collected their responses and analyzed the data, and finally we compared the results against our classification framework.

Chapter 2 Literature Review

After many years of development, VRL continues to be a significant challenge [3], [4]. We conducted a literature review to provide insights into the difficulties involved. The goals of our study were to understand the issues and discuss the issues based on a unified platform.

2.1 VRL Challenges

The user-centric VRL challenges of sickness, presence, and fatigue were identified through our research. For each of these aspects, there has been extensive studies throughout the history of VR, and their continued appearance suggests that they are fundamental challenges. Although there has been research focusing on each of these aspects, often the relationships between them has not been the primary focus.

2.1.1 Sickness

Since VR sickness is a conspicuous problem, it has been extensively researched. Early research built on studies about flight simulator sickness, as both syndromes are like motion sickness [5]. VR sickness and motion sickness have the same symptoms, such as dizziness, disorientation, sweating, salivation, nausea, and vomiting, and amongst those experiencing it no symptom predominates. Additionally, only certain number of people are susceptible to experiencing it. However, incidences of VR sickness were found to be less severe and occur less frequently than that of motion sickness [6].

Originally proposed by Reason and Brand in 1975 [7], the sensory conflict theory is widely accepted to be the cause of VR sickness. The theory states that our mental model of motion is comprised of input from audio, visual, proprioceptive, and vestibular senses, and that

incongruent input causes motion sickness symptoms. The vestibular sense comes from fluid filled semicircular canals of the inner ear, which detect acceleration, and the proprioceptive sense comes from muscles, tendons, and joints, which detect the effort being employed by one's own body parts. Sensory conflict occurs when VR provides for the audio and visual senses, while the vestibular and proprioceptive senses are still governed by the real-world.

Early efforts to eliminate VR sickness centered around accurately tracking the HMD [8]. There must be extreme fidelity between user's head movement and what the HMD displays or else a sensory incongruity will occur. Research showed that tracking errors and latency dramatically increasing the occurrence of simulator sickness. The hardware capabilities of current generation HMDs, such as resolution, framerates, field of view, and latency, have immensely decreased this kind of sensory conflict [9].

Despite these technological advancements, VRL still has the potential for causing sickness [10]. A sensory conflict can occur when moving in an infinite-scale virtual world, while remaining in the confines of a room-scale real world. Some VRL methods attempt to reducing sensory conflict by restricting the user's field of view while in motion [11]. This forces the user to focus on the non-visual senses rather than the visual ones. However, these attempts also reduce the amount of presence the user feels.

2.1.2 Presence

Books, movies, and video games can hold a user's attention and emotion, but VR is different. VR promises to let the user experience a virtual world as though it were real, psychologically existing elsewhere without changing their physical location [12]. This concept is intuitive but hard to describe, so several researchers have made attempts to disambiguate terms and ideas.

In 1997, Slater and Wilbur made a distinction between presence and immersion which became widely accepted [13]. Presence is the subjective and is a psychological description of a user's sense of being in a virtual world. On the other hand, immersion is objective and is technological description of aspects VR system that can produce a sense of presence. To increase presence there has been continued development of immersive technology, such as, resolution, framerates, field of view, graphics, and tracking fidelity.

Heeter identified that users can feel three types of presence: personal, social, and environmental [14]. Personal presence is the amount a user feels self-embodiment in the virtual world, which requires some virtual representation of the physical self. Social presence is the feeling that other beings exist in the virtual world, which requires other users or artificially intelligent agents. Environmental presence is the amount that the virtual environment acknowledges the user which, requires the virtual world to be interactable [15].

Aside from increasing user enjoyment in VR, high levels of presence can also improve user performance in tasks such as spatial understanding, memorization and training. The human brain is optimized for three-dimensional information, so naturally interacting in three dimensions can reduce information clutter and increase information bandwidth [12].

Sickness and presence have long been identified as fundamental challenges of VRL. As a result, when researchers propose a new VRL method users levels of sickness and presence are usually reported [10], [16]. Some research has even examined the trade-off between sickness and presence by comparing different VRL methods [17]. These results point to the need of a common discussion platform for analyzing the challenges of sickness in conjunction with presence.

2.1.3 Fatigue

Compared to sickness and presence, research has been less focused on the VR fatigue, with early VR ergonomics research focusing on the immediate comfort of the HMD [18]. This makes sense because fatigue is not as obvious of a problem as sickness or presence, since it only occurs after continued use of a VR system. For this reason, much of our study of the subject is based on results from the larger field of human computer interaction (HCI).

In the context of HCI, physical ergonomics consists of two components, musculoskeletal repetitive strain injuries and general energy expenditure coupled with fatigue [19]. Muscular fatigue is when the muscle cannot produce its maximum force, and it is measured by the total mechanical energy expenditure of a muscle from activations integrated over time. Which simply means increased motion overexerts users quicker.

The physical fatigue of HCI has been studied since as a problem since the proliferation of natural user interfaces. Above-the-waist gestural interfaces such as the Kinect [20] and touchscreens caused some users to develop “Gorilla Arm”, prompting research into design guidelines after they were produced [21]. Cutting-edge interfaces can be prone to poor ergonomics because pressure from competitors continuously shrink their time-to-market period. This does not allow thorough ergonomics assessment, which results in products either providing poor ergonomics or completely shifting ergonomic decisions to the end-user without giving any warning or recommendation [19].

If only sickness and presence are considered, then an omnidirectional treadmill would be an ideal VRL method [22]. However, intuition tells us that running on a treadmill could not be sustained for an extensive amount to time. Not surprisingly, HCI research on fatigue shows that

it is an important factor of ergonomic usability and it should not be ignored [23]. Despite it being a fundamental VRL challenge, the relationship between fatigue and either sickness or presence has not been studied.

2.2 VRL Classification

The previous section highlights the need for a platform that enables comparative discussion of the three VRL challenges of sickness, presence, and fatigue. Such a framework would allow the three user-centric factors to be studied, discussed, and contrasted within a uniform context, instead of independently.

One approach to establishing such a platform is via the derivation of a classification system to categorize and organize VRL methods. With an organization framework, discussions can then be carried out on related VRL methods. VRL classification has been attempted before, but existing frameworks were based on the implementations of VRL methods, rather than being focused on these user-centric factors.

2.2.1 Previous Classifications

The existence of various VRL methods has prompted previous classification attempts by researchers. To gain an understanding of existing methods, researchers categorized them by breaking them down into lower-level components. Since each classification attempts decomposed VRL into different low-level components, the resulting classification frameworks were different, but they all were focused on a similar goal.

In 1997, Bowman et. al. proposed a taxonomy of VRL methods based on user interactions. In this classification VRL was broken down into direction selection, acceleration selection, and input conditions [24]. In 2002, Arns classified VRL methods based on the rotation

and translation of the locomotion, with each component being either physical or virtual [25]. In 2017, Boletis characterized VRL methods based on interaction type, the motion type, and interaction space [2].

2.2.2 Strengths and Limitations

These classifications attempted to create a standardized description that would clearly categorize and distinguish different VRL methods. By providing a common language to compare the functionality of different methods, these are useful tools for describing aspects of VRL. However, these frameworks were created to capture the specific implementations of existing VRL methods.

These technology-dependent classifications allow for existing methods to be analyzed and discussed, but it also limits the framework to the state of technology at the time. As a result, previous classifications do not suggest protentional directions for future VRL methods. To enable finding the search for improved methods, a classification framework should describe the characteristics of better VRL solutions.

Chapter 3 User-Centric Classification

The literature review of the previous chapter demonstrates the need for a classification of VRL methods such that distinct methods can be compared within a common context. Such a framework should address the fundamental challenges of VRL independently from the state of existing technology and facilitate the search for better VRL methods.

3.1 Proposed Framework

This thesis proposes the User-Centric Classification (UCC) framework for identifying, discussing, and comparing characteristics of VRL methods. In the UCC framework each of the

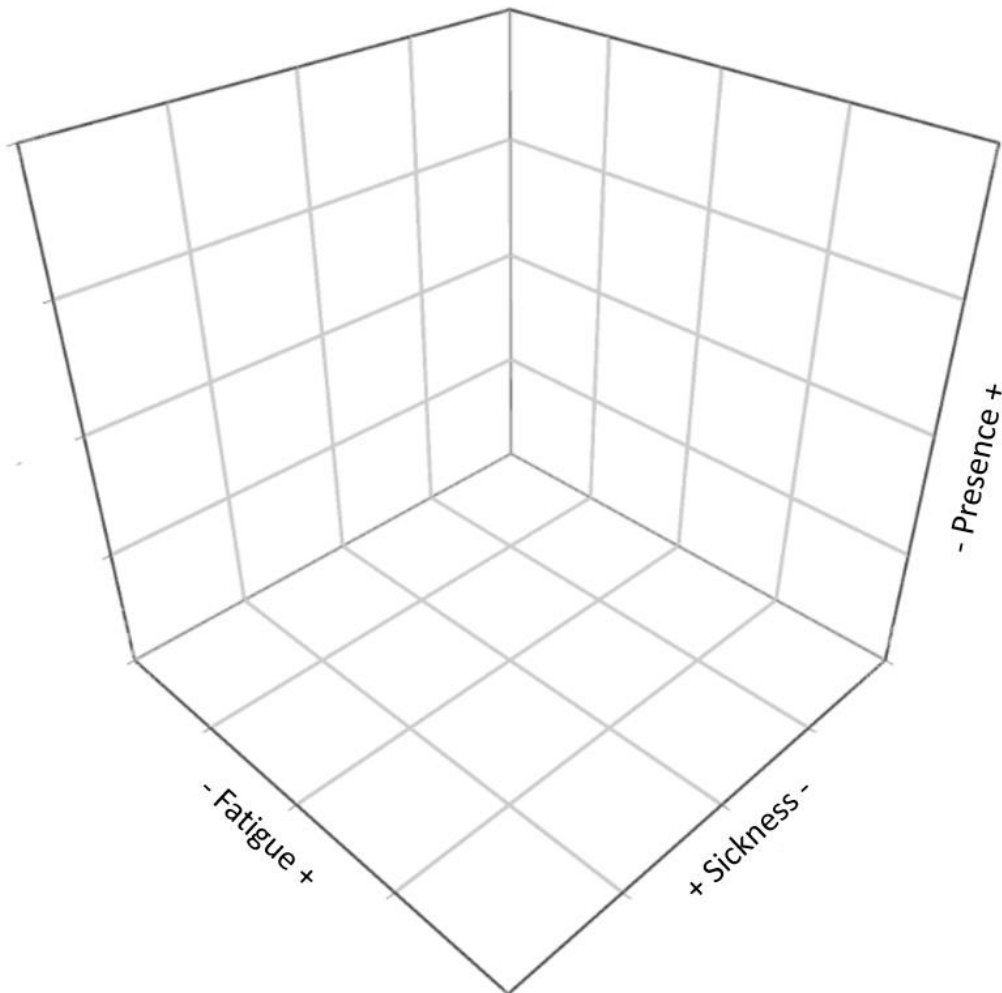


Figure 1. User Centric Classification (UCC) Framework

fundamental VRL challenges of sickness, presence, and fatigue, become metrics to classify VRL methods. Determining how well a method satisfies the three VRL challenges will determine the UCC metrics.

To support the consideration of all three VRL challenges in conjunction with each other, we present an aid for visualizing the UCC framework. As illustrated in Figure 1, we created a three-dimensional graph to plot VRL methods, with each axis representing a fundamental VRL challenge. By determining the UCC metrics of a VRL method, that method can be plotted in

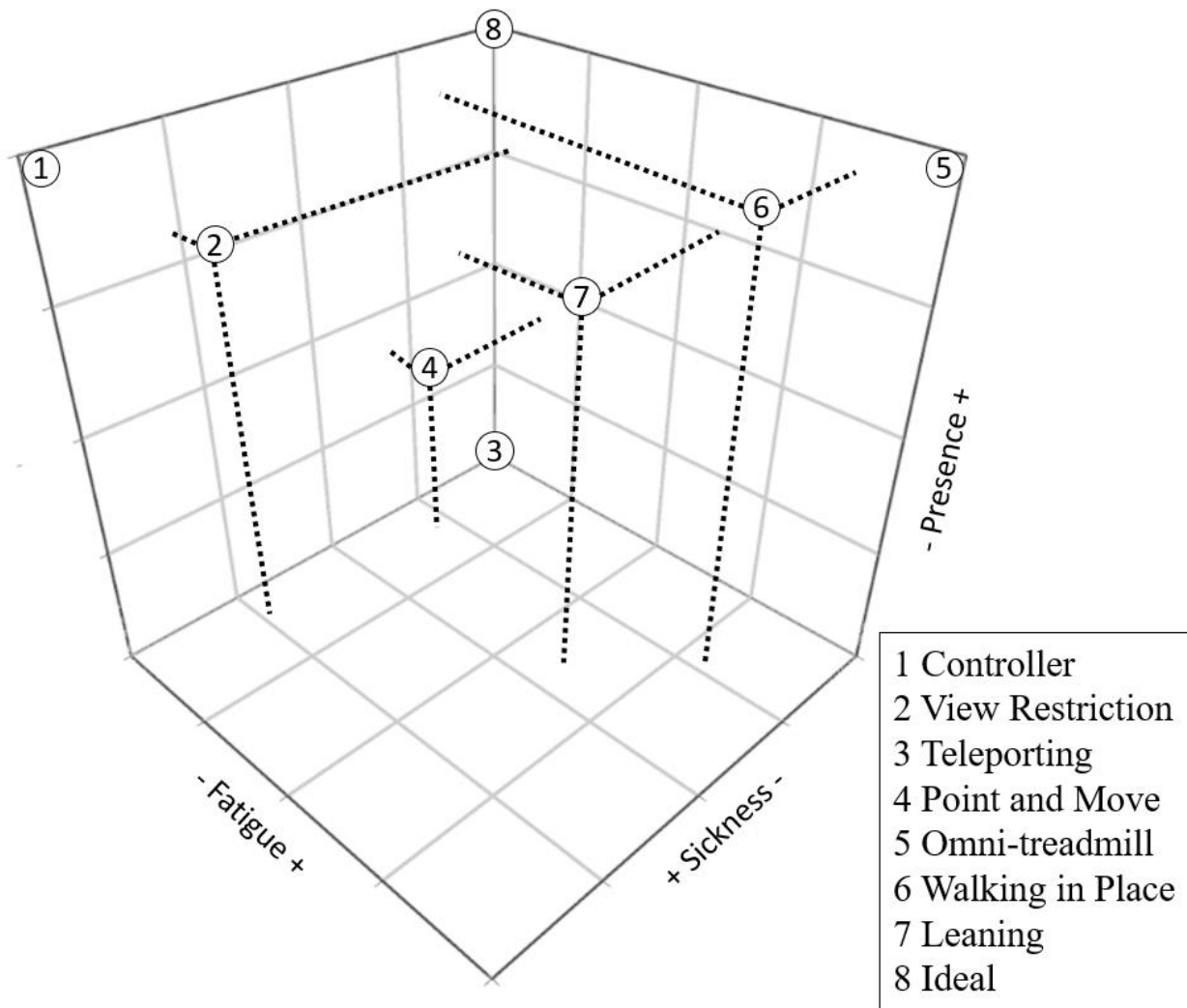


Figure 2. VRL Methods in UCC Framework

three-dimensional space. Using the UCC framework to plot several VRL methods in this way, allows for relative comparison of the overall performance of a method.

By using this framework, new VRL methods can be compared with current methods, and we can systematically search for the ideal VRL solution. In this framework, the theoretically ideal method would have the lowest occurrences of sickness, the highest level of presence, and lowest incidences of fatigue. The three fundamental problems with VRL are well suited to serve as metrics for classifying current and future VRL methods because it creates a classification framework that is rooted in the human experience, which means it is more perennial than classifications based on current technological capabilities of VR systems.

3.2 Existing VRL Methods

We conducted a literature review on how well existing VRL methods solve the three user-centric VRL challenges. Based on previous research, we classified several VRL methods within the UCC framework. Figure 2 shows this classification plotted on a three-dimensional graph, with each axis representing an estimation of a different metric. The following is an explanation of each method and our reasoning for classification.

1. **Controller-** The user moves with a handheld controller or gamepad. This method results in high sickness, high presence, and low fatigue [26].
2. **Field of View Restriction-** The user still moves with a controller or gamepad, but the user's field of view is restricted while in motion. In comparison to controller, this method results in lower sickness, lower presence, and similar fatigue [11].
3. **Teleporting-** The user selects a visible nearby location and teleports there instantly. This method results in low sickness, low presence, and low fatigue [27].
4. **Point and move-** The user still selects a nearby location, but instead of teleporting there instantly the user slowly moves to the selected location. In comparison to teleportation, this method results in higher sickness, higher presence, and similar fatigue.

5. **Omnidirectional Treadmill-** The user walks on an omnidirectional treadmill, moving in the direction they are walking. This method results in low sickness, high presence, and high fatigue.
6. **Walking in Place-** The user walks in place, moving in the direction they are facing. In comparison to an omni directional treadmill, this method results in higher sickness, lower presence, and slightly lower fatigue [28].
7. **Leaning-** The user leans in a chair controller, moving in the direction they lean. In comparison to walking in place, this method results in higher sickness, lower presence, and lower fatigue [29].
8. **Ideal-** This a theoretical a method that is yet to be discovered. This method results in low sickness, high presence, and low fatigue.

3.3 Framework Analysis

By comparing VRL methods the UCC framework, a trade-off appears to emerge. The controller has low fatigue and high presence but causes sickness. Teleportation maintains low fatigue and solves for sickness but sacrifices presence. Walking doesn't cause sickness or break presence but causes fatigue.

The problem with using literature review for UCC is that there is no common basis for comparison. Disparate research results provide no commonality for metric data, so the relative positions of the VRL methods can only be articulated based on intuition. This is the reason why the metrics in Figure 2 have no numerical data prescribed to them. In most cases, research focuses on only one of the VRL challenges, so in those cases, anecdotal experience and intuition were used to fill in the gaps.

To address these challenges, we chose to conduct an experiment to further verify and demonstrate the strengths of the UCC framework. The experiment should test VRL methods in a uniform way to enable metric comparison, and it should test all UCC metrics simultaneously to

capture trade-offs that occur. If successful, we will show that VRL methods produce different UCC metrics and that we can capture and compare those metrics in meaningful ways.

Chapter 4 The Testbed

In order to test the validity of our classification framework, we used the testbed evaluation philosophy advocated by Bowman et al [30]. Creating a testbed environment in which many VRL methods could be tested while holding other variables constant. The better our testbed can elicit the UCC metrics the more accurate the resulting classification will.

4.1 Testbed Implementation

Our UCC testbed was developed using the Unity2017 game engine. Unity was chosen due to the availability of VR software support. Several free unity game assets were acquired from the Unity Asset Store, with the Low-Poly Park and Low Poly Sci Fi Set being used extensively. Finally, this project could not have been completed on time without the Virtual Reality Toolkit (VRTK). The VRTK was an open-source collection of useful scripts and prefabs for building VR solutions rapidly in Unity [31]. The complete list of the software assets can be found in Appendix A.



Figure 3. VR Locomotion Testbed

Figure 3 shows the implemented testbed. The labels identify areas in the order that a user would encounter during testing, with each area being included for different reasons. The following is an explanation of each destination area and its purpose in the testbed.

1. **Outdoor Park-**The user begins testing in this location. In this area, the user can clearly see the outdoor the scene of the park. This was included because focusing on a distant stationary object can reduce **sickness** [32].
2. **Lamppost Path-**The user then navigates the lamppost path. In this area, when the user gets near a lamppost it illuminates. This was included to allow users to get used to the environment and to give users a **goal**.
3. **Throwing Food-** The user throws food into the canyon. In this area, the user picks up a food item from a table, brings the item to a canyon overhang, and throws the item into the canyon. This was included because interacting with the environment increases **presence** [14].
4. **Crossing Canyon-** The user must cross the canyon. In this area, the user can choose to cross via the narrow bridge or the wide ledge. This was included because the height can induce vertigo increasing **sickness** [32].
5. **Indoor Bunker-** The user enters an underground bunker. In this area, doors automatically open and the user can go inside. Since it is an enclosed space, the walls occupy most of the user's field of view, increasing sensory conflict. This was included because the absence a distant object to focus on increases **sickness** [33].
6. **Hallway Map-** The user passes a map in a hallway. In this area, the user can identify a map with the location of the key within the bunker. This was included because being able to obtain information during locomotion indicates increased **presence** [30].

7. **Bunker Maze-** The user searches for key to treasure chest. In this area, the bunker acts a maze testing the user's spatial awareness and orientation. This was included because increased spatial awareness indicates increased **presence** [24].
8. **Treasure Chest-** The user completes the test at the treasure chest. In this area, the user uses the key they found in the bunker to open the treasure chest and pick up the jewel that is inside. This was included to give the user an accomplishable **goal**.

Our testbed implementation was designed to adequately test UCC metrics based on literature review. The testbed engages the user with initial and final goals to accomplish (areas: 2, 8), while creating the potential for sickness (area: 4, 5), and presence (area: 3, 6, 7). An average user should be able to complete the test within a few minutes, which should be sufficient for inducing some fatigue. We felt the resulting implementation would sufficiently test the framework metrics.

Eliciting the UCC metrics of fatigue and sickness presented two practical limitations to the testbed design. First, the ability to induce fatigue is limited. Designing the testing duration to be too short will not cause fatigue, while a longer test discourages volunteers and may be impractical to test. Second, the extent for assessing sickness is restricted. Inducing too little sickness will not adequately test the metric, while inducing too much would result in sickness prone users unable to complete the test.

4.2 VRL Method Implementation

After completing the testbed, the next step was to allow users to navigate the virtual environment by implementing VRL methods. Implementing all existing VRL methods would be beyond the scope of this project and subjecting users to testing each method would not be practical. We

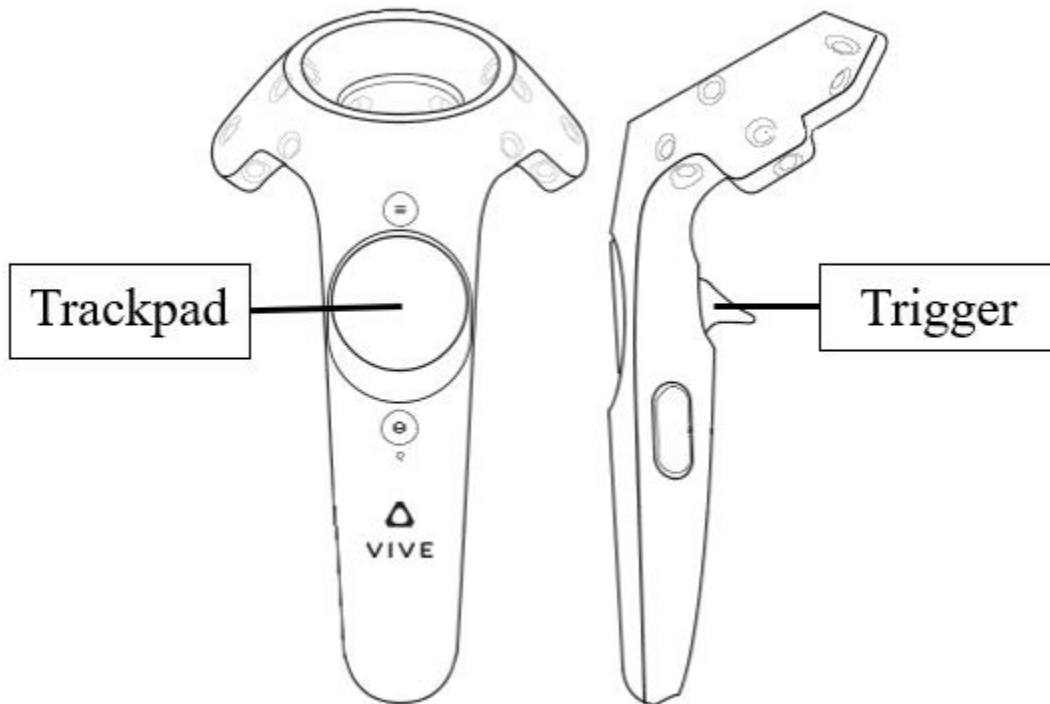


Figure 4. Vive Controllers

chose to implement three dissimilar VRL methods, controller, teleportation, and walking in place because these are the most popular methods currently used. More importantly, these methods were chosen because their resulting UCC metrics would be the most pronounced.

The HTC Vive was chosen to be used for the experiment because we had more familiarity with it. Other current generation VR systems have similar technical specifications, so the choice of VR system should not affect the results [9]. The Vive controller's specific button layout is depicted in Figure 4 [34]. For all the VRL methods, rotation in virtual space was controlled by tracking physical orientation, while grasping virtual objects was controlled by pressing the trigger button. To keep the controls similar, each VRL method was initiated by using the thumb on the trackpad. The specific controls of the three implemented methods are as follows.



Figure 5. Using Controller Method



Figure 6. Using Teleport Method

Controller - The user presses the trackpad with the thumb then sliding it on the trackpad initiates locomotion. The speed of the locomotion is determined by tilt angle of the controller. The



Figure 7. Using Walking Method

direction of travel is determined by the direction in which the controller is pointed. The use of this method is illustrated in Figure 5. In the lower right corner, the user can be seen with an out-reached hand while issuing the walk forward command.

Teleport - The user presses the trackpad with the thumb to activate a pointer. Using the pointer, the user selects a valid location in the virtual world. When the thumb is released, the user instantly teleports to the position that he or she was pointing to. The use of this method is illustrated in Figure 6. The green arch target indicates where the user is pointing, and the green dot gives the user a sense of where they are going travel.

Walking - The user presses the trackpad with the thumb while simultaneously walking in place to initiate locomotion. The speed of the locomotion is determined by the vertical motion of the HMD. The direction of travel is determined by the direction of the controllers. The use of this

method is illustrated in Figure 7. In the lower right corner, the user can be seen with hands close to chest in a natural running position.

Chapter 5 VRL Method Assessment

We developed a testing procedure to assess the implemented VRL methods within the common testbed. We had users test the VRL methods, and we captured the UCC metrics by asking them questions about their experience.

5.1 Metric Questionnaires

Parts of the testbed were designed to elicit metrics in the classification framework, and the questionnaires are instruments to measure the user's assessment of the metric. All the questionnaires consisted of four Likert item questions ranging from 1 (not at all) to 4 (extremely). The general strategy to constructing the questionnaires was to minimize the number of questions by adopting sub-sets of established questionnaires for each metric based on existing research studies. Specifics on the source and selection of the questions are as follows.

Did you feel nauseous?
Did you get indigestion or burp?
Did you feel dizzy?
Did you get a headache?

Table 1. Presence Questionnaire

Sickness Questionnaire- Table 1 contains the sickness questionnaire. These questions were adopted from the simulator sickness questionnaire, developed by Kennedy et al [35]. This has been the de facto method in studying VR sickness since being proposed in 1993. The vertigo question was not used because users didn't understand the concept, and the sweating question was not used because it could result in a false positive for fatigue.

Did you feel you were actually in the virtual space?
Did you lose awareness of the real world?
Did you get a sense of the distance & scale?
Did you get a sense spatial relation & orientation?

Table 2. Presence Questionnaire

Presence questionnaire- Table 2 contains the presence questionnaire. These questions were selected from the IGroup presence questionnaire [36] developed by Schubert et al [37]. We chose not to use the Witmer and Singer presence questionnaire [38] because it focuses more on evaluating an application’s immersion rather than on the user’s presence.

Did you feel it was hard to move around the virtual space?
Did you find the navigation mentally demanding?
Did you find the navigation physically strenuous?
Do you think continued use would leave you exhausted?

Table 3. Fatigue Questionnaire

Fatigue questionnaire- Table 3 contains the fatigue questionnaire. Unlike sickness and presence, there is not a common questionnaire for fatigue while using VR. Even in the broader field of human computer interaction, there isn’t a standard usability questionnaire [39]. To address this gap, we created our own four questions. These questions were modeled after various medical fatigue [40] and computer usability questionnaires.

5.2 Testing Protocol

Before testing began, the functional components of the VR system were explained to the user. As well as safety concerns including inadvertent real-world collisions and cord entanglement. Users were then asked to assess their likelihood of motion sickness, experience with video games, and experience with VR on a scale of 1 (none) to 4 (extensive). To maintain a respectful collection of data, the only recorded user demographic was age.

Before using each VRL method, the user was instructed on its use. The user completed the entirety of the testbed course, using each of the VRL methods one at a time. To remove testing order bias, the VRL method testing order was chosen randomly, and each method had an equal number of users testing it as the first, second, and third method. After testing a method, the user responded to the described sickness, presence, and fatigue questionnaires. The questionnaires were also asked in a random order to remove any bias.

After using all the methods, users were asked to comparatively rank the three VRL methods based on the level of sickness, presence and fatigue they experienced. These comparison questions were valuable because after using all the VRL methods users could fully understand the differences between the methods. Additionally, they were asked to rank the methods based on which felt the most like “virtual reality” and which they would prefer to use. The complete list of the questions asked can be found in Appendix B.

5.3 User Testing

In total 30 users were tested, with the testing and questions taking 15-25 minutes per user. We tried to strike a balance between getting enough data from users and being burdensome for the users. To keep variables to a minimum, all the user testing was conducted on a Dell Inspiron

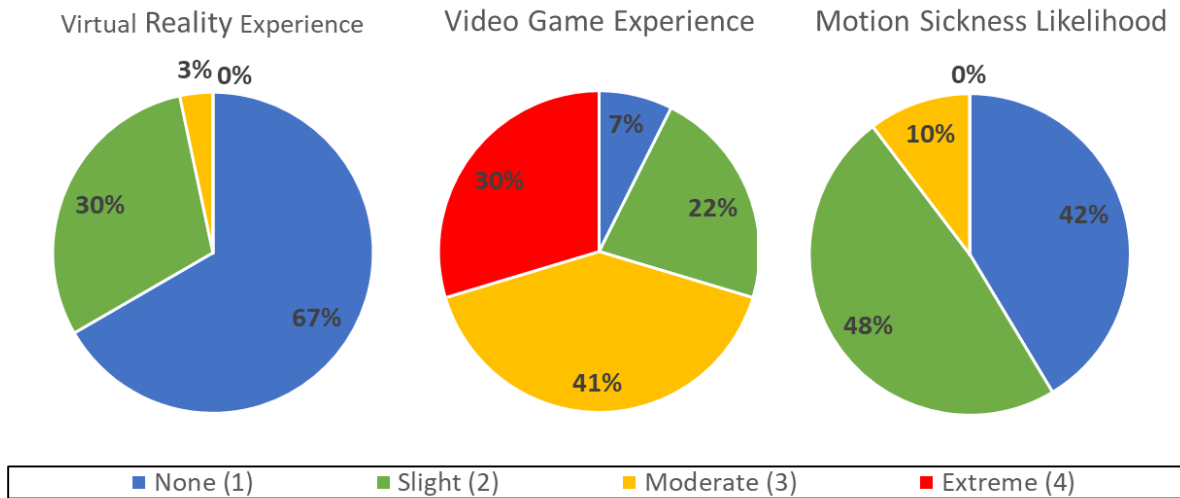


Figure 6. User Background

7577 laptop, with a 6GB NVidia GTX 1060. This powerful gaming laptop satisfied the demanding system requirements of the HTC Vive.

The laptop's portability enabled easy setup in several testing locations, including a research lab on our campus, a comic-book store, and an office space. Testers were recruited by the author by approaching people present at these locations and asking them if they would like to test a VR system. Multiple testing locations allowed us to gather data on different users with varied demographics, with the users differing in race, gender, occupation, and socioeconomic status. Users ages ranged from 8 to 50, with an average age of 29 years old.

Before testing, users were asked questions about their background that could affect UCC metrics. A summary of this data is illustrated in Figure 8. The pie chart on the left shows that a large majority of users never used a VR before; The middle pie chart shows that the majority have moderate or extensive videogame experience; The pie chart on the left shows that no users reported being extremely susceptible to motion sickness.

Chapter 6 Results

The data collected from testing was analyzed in Excel using the Data Analysis Toolpack[41] and Real Statistics Resource Pack [42]. The Kruskal-Wallis test was used instead of one-way ANOVA because the Likert-type questionnaire and method ranking data was not suitable for parametric analysis. Similarly, the non-parametric Nemenyi test was used for post-hoc analysis. The complete raw data we collected is available in Appendix C.

6.1 Questionnaire Results

As discussed, after testing each VRL method, users were asked the corresponding UCC metric questionnaire. Recall that the questionnaires for each metric consisted of four Likert item questions ranging from 1 (not at all) to 4 (extremely). Following the methods of previous studies [43], the Likert items in each questionnaire were summed to produce a Likert scale for each UCC metric, resulting in values ranging from 4 to 16. There were 30 users that each tested the three VRL methods, for a total of 90 data points.

	Minimum	Maximum	Average	Standard Deviation
Controller	4	10	5.66	1.81
Teleport	4	9	4.50	1.11
Walking	4	13	5.33	1.81

Table 4. Sickness Questionnaire

	Minimum	Maximum	Average	Standard Deviation
Controller	7	16	13.63	2.02
Teleport	9	16	13.10	2.27
Walking	12	16	14.80	1.4

Table 5. Presence Questionnaire

	Minimum	Maximum	Average	Standard Deviation
Controller	4	12	6.73	2.46
Teleport	4	12	5.26	1.73
Walking	4	14	8.36	2.49

Table 6. Fatigue Questionnaire

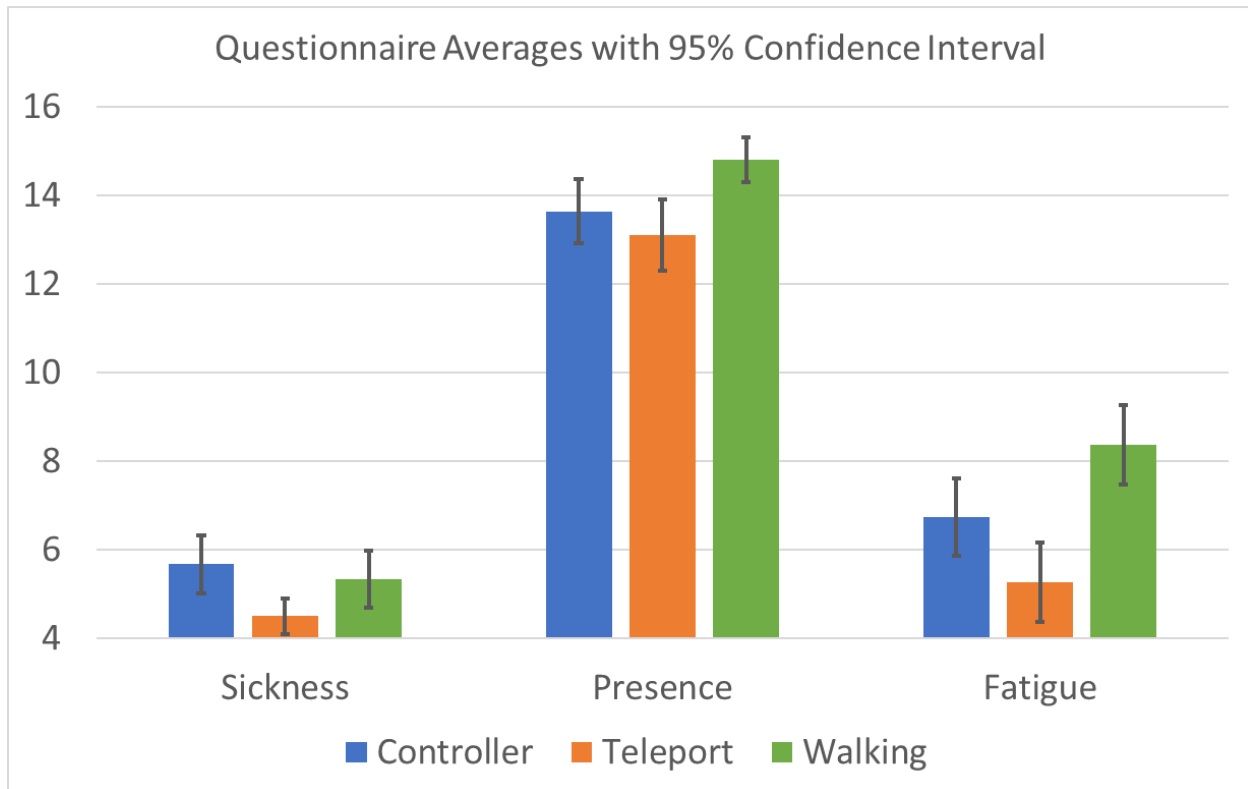


Figure 7. Questionnaire Averages

6.1.1 Data Summary

Tables 4, 5, and 6 show a summary of sickness, presence, and fatigue questionnaire data. Each table shows the maximum score, the minimum score, the average score, and the standard deviation for the corresponding questionnaire responses. The bar graph in Figure 7 shows the mean of each metric for the tested VRL methods. The error bars show the 95% confidence interval of the true mean of the population.

	Sickness	Presence	Fatigue
P-Value	5.04×10^{-3}	7.57×10^{-3}	8.47×10^{-6}

Table 7. Kruskal-Wallis Significance of Questionnaires

Methods Compared		Sickness	Presence	Fatigue
Controller	Teleport	1.37×10^{-2}	7.01×10^{-1}	4.57×10^{-2}
Controller	Walking	8.50×10^{-1}	8.21×10^{-2}	4.57×10^{-2}
Walking	Teleport	5.92×10^{-2}	9.39×10^{-3}	7.18×10^{-6}

Table 8. Nemenyi Pairwise Significance of Questionnaires

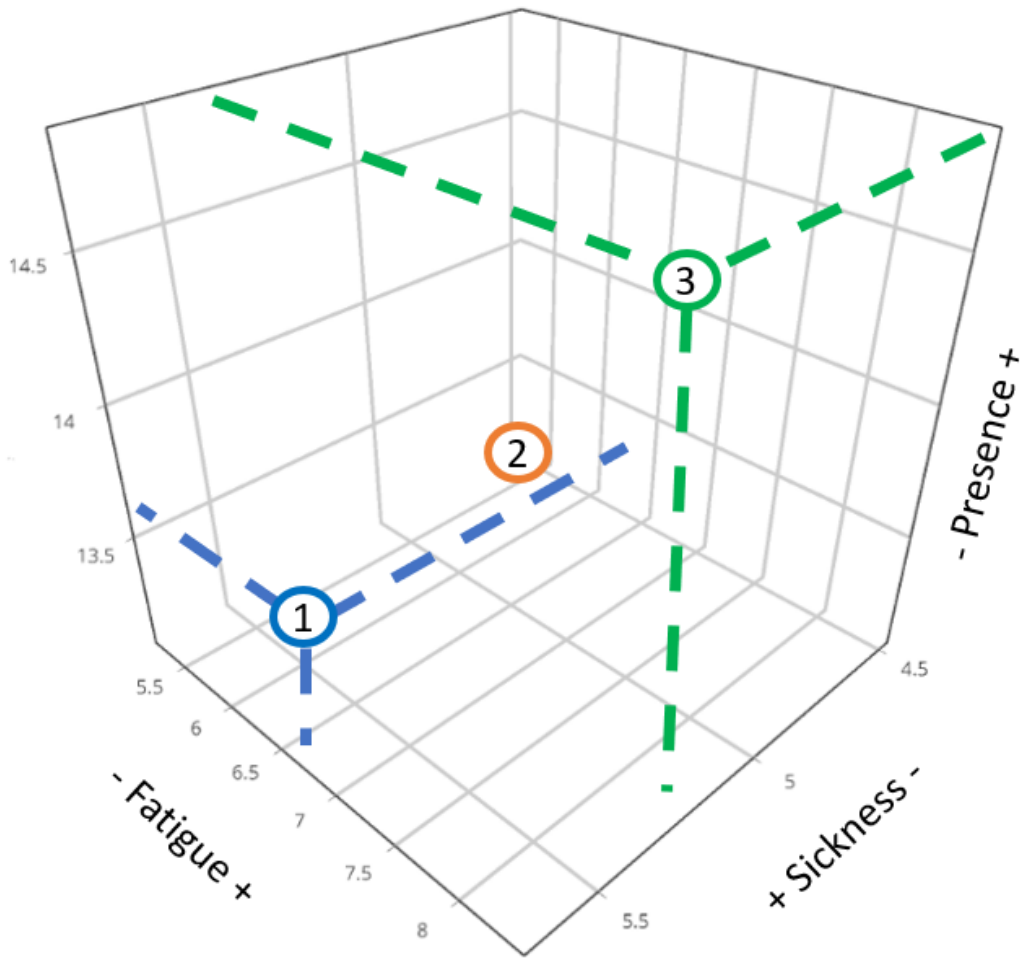
For each UCC metric, a Kruskal-Wallis between-groups test was conducted to test the hypothesis that VRL methods affected the questionnaire data, with the resulting p-values shown in table 7. These three tests indicate that there was a statistically significant effect on UCC metrics for the three VRL methods. For each Kruskal-Wallis test, Nemenyi post-hoc analysis was conducted to evaluate the pairwise differences. As illustrated in table 8, four of the resulting p-values show some differences are statistically insignificant. In the table, large p-values are highlighted in red (0.71 and 0.85) and marginal p-values are highlighted in yellow (0.059 and 0.082).

6.1.2 Data Analysis

The data in Table 4 and the leftmost three bars in Figure 7, show that sickness questionnaire scores are all very low. We believe this occurred because we did not induce enough sickness in our testbed. Due to concerns about the well-being of our testers, the testbed avoided overly inducing sickness. However, it appears that we may have over. Conversely the data in Table 6 and the middle three bars in Figure 7 presence questionnaire scores are very high.

We believe that this occurred because the high level of presence induced by current generation VR systems.

Referring to Table 8, for sickness, the controller and walking comparison resulted in $p=0.85$. This statistical insignificance is possibly due to the testbed not being able to induce and capture sickness adequately. For presence, the controller and teleport comparison resulted in the statistically insignificant result of $p=0.71$. This may be due to 67% of users had no prior VR experience before testing. Without a basis for comparison, if a user reported maximum presence on the first method but experienced higher presence on subsequent methods, they were unable to score the results properly. Even with these concerns, as shown in the next section, using this data for UCC assessment can enable a meaningful discussion.



	Sickness	Presence	Fatigue
Controller ①	5.66	13.63	6.73
Teleport ②	4.50	13.10	5.26
Walking ③	5.33	14.80	8.36

Figure 8. Questionnaire Averages in UCC Framework

6.1.3 UCC Assessment

The average scores from each questionnaire, shown in table 4, 5 and 6, were used as metrics to classify the VRL method in the UCC framework. Figure 8 shows the results in a three-dimensional UCC plot. Comparing Figure 8 to our literature based UCC classification in Figure 2, the relative positions exhibit similarities. In Figure 8 it should be noted that the axis have very

different scales, so a numerically large difference in one metric can appear the same as a numerically small difference in another metric. The UCC framework’s strength comes from the ability to compare VRL methods relative to each other, and this plot should be used as a visualization for that comparison.

6.2 Ranking Results

After testing all the methods, users were asked to comparatively rank the three VRL methods based on the level of sickness, presence and fatigue they experienced. For each UCC metric, the methods were ranked between 1 (least) to 3 (most). There were 30 users that each ranked the three VRL methods, for a total of 90 data points.

	Mode	Average	Standard Deviation
Controller	3	2.43	0.66
Teleport	1	1.53	0.76
Walking	2	2.03	0.75

Table 9. Sickness Ranking

	Mode	Average	Standard Deviation
Controller	2	1.96	0.75
Teleport	1	1.40	0.55
Walking	3	2.63	0.60

Table 10. Presence Ranking

	Mode	Average	Standard Deviation
Controller	2	2.03	0.54
Teleport	1	1.16	0.45
Walking	3	2.80	0.40

Table 11. Fatigue Ranking

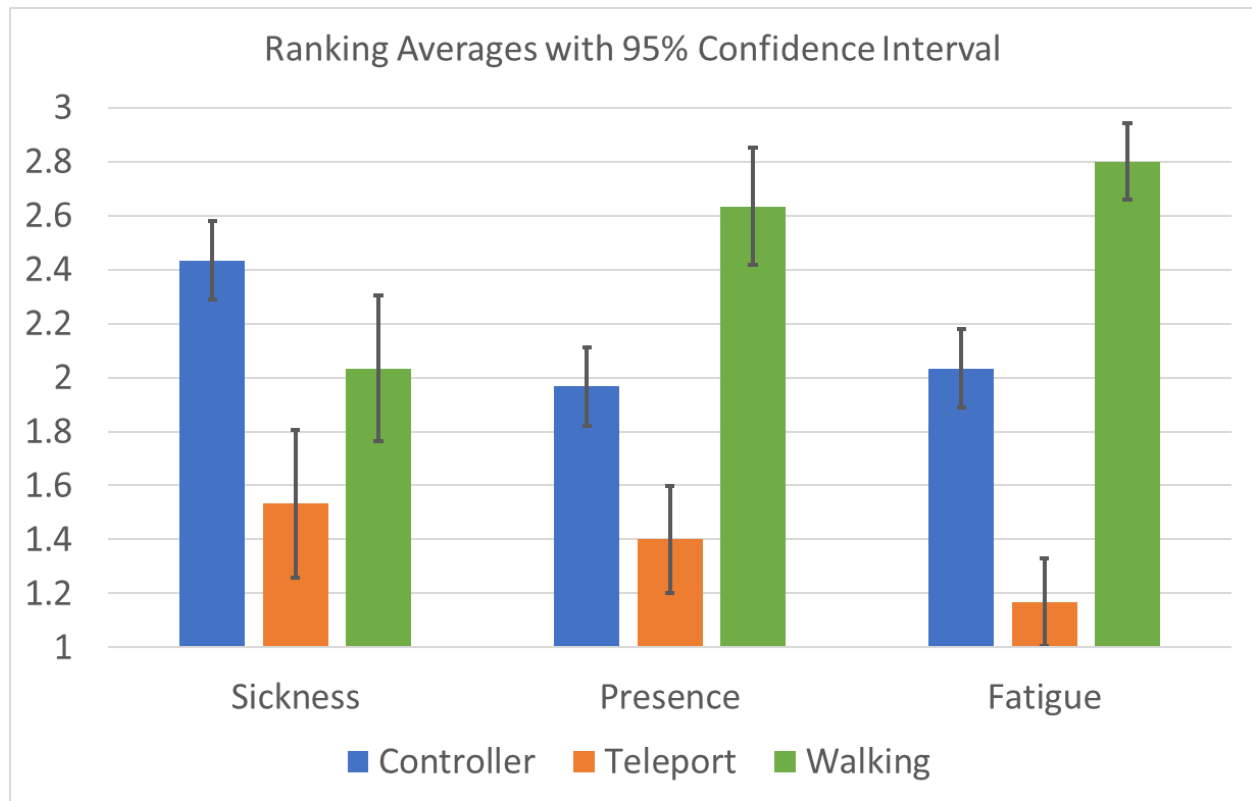


Figure 9. Ranking Averages

6.2.1 Data Summary

Tables 9, 10, and 11 show a summary of sickness, presence, and fatigue ranking data. Each table shows the mode (most frequent ranking), average ranking, and standard deviation and for the corresponding metric data. The bar graph in Figure 9 shows the mean for each metric for the tested VRL methods. The error bars show the 95% confidence interval of the true mean of the population.

	Sickness	Presence	Fatigue
P-Value	1.18×10^{-4}	4.31×10^{-8}	1.24×10^{-13}

Table 12. Kruskal-Wallis Significance of Ranking

Methods Compared		Sickness	Presence	Fatigue
Controller	Teleport	2.14×10^{-4}	3.22×10^{-2}	3.87×10^{-4}
Controller	Walking	1.78×10^{-1}	8.90×10^{-3}	2.03×10^{-3}
Walking	Teleport	6.82×10^{-2}	2.00×10^{-7}	4.50×10^{-12}

Table 13. Nemenyi Pairwise Significance of Ranking

For each UCC metric, a Kruskal-Wallis between-groups test was conducted to test the hypothesis that VRL methods affected the ranking data, with the resulting p-values shown in Table 12. These three tests indicate that there was a statistically significant effect on UCC metrics for the three VRL methods. For each Kruskal-Wallis test, Nemenyi post-hoc analysis was conducted to evaluate the pairwise differences. As indicated in Table 8, two of the resulting p-values show differences are statistically insignificant. In the table, the large p-value is highlighted in red (0.17) and the marginal p-value is highlighted in yellow (0.068).

6.2.2 Data Analysis

As illustrated in Figure 9, the ranked data is much more stratified when compared to the fine scale of questionnaire data in Figure 7. For questionnaire responses, a user could perceive a small difference but potentially respond the same for all methods, but the ranked data was collected from users differently than the questionnaire data. The comparison questions were asked after all the VRL methods were tested so that the users could fully understand the differences between the methods. Requiring users to rank the methods allowed for differentiation even if the perceived difference is small.

Referring to Table 13, for sickness, the controller and walking comparison resulted in $p=0.17$. As discussed, a testbed deficiency in eliciting the sickness metric may have caused this statistical insignificance. It may be that there is no difference between these implementations of

walking and controller in the context of inducing sickness. Being able to compare VRL methods though their similarities and differences of their UCC metrics, demonstrates the usability of the UCC framework.

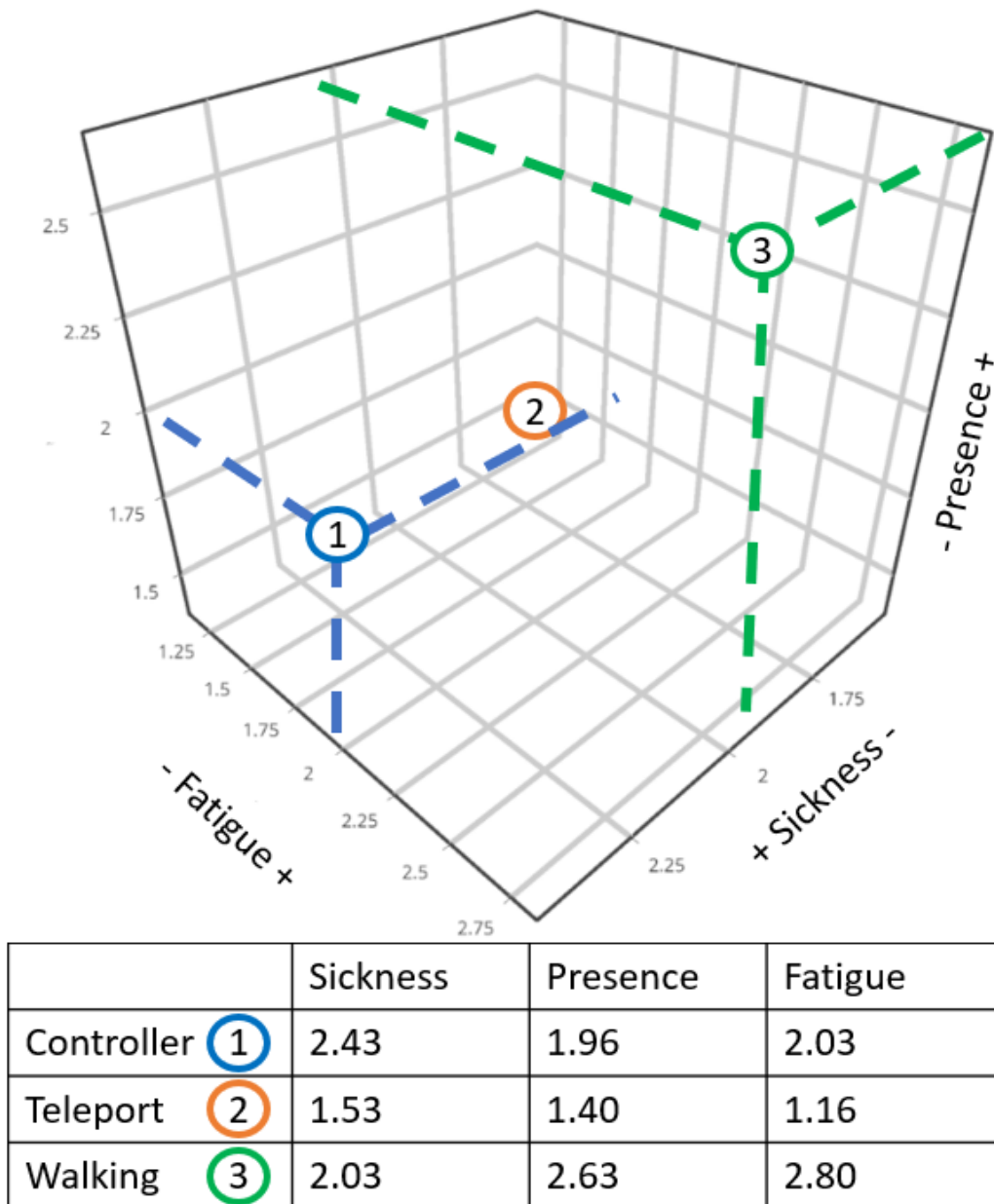


Figure 10. Ranking Averages in UCC Framework

6.2.3 UCC Assessment

The average rankings for each metric, shown in Table 9, 10 and 11, were used as metrics to classify the methods in the UCC framework. Figure 10 shows the results in the UCC three-dimensional plot. Again, it is important to note that each dimension in Figure 10 has a different scale, and that the plot should only be used for comparing the relative positions of the VRL methods. Note that in Figures 8 and Figure 10 the relative ordering of the three VRL methods are in the same relative positions. It is interesting to note that UCC is capable of capturing user's preferences, whether they were asked opinion questions or to explicitly rank the methods.

6.3 Discussion

Through this study we have demonstrated the strength and usability of the UCC framework. By implementing a common testbed, we were able to induce sickness, presence, and fatigue in users within a uniform environment. We showed that different VRL methods produce different UCC metrics and that those metrics can be captured.

Contrasting the three methods with respect to the UCC metrics allowed us to discuss and compare methods in a meaningful way. When attempting to compare these methods, some did not produce statistically significant results. We believe this has been caused by deficiencies in the testbed design. It may also be possible that our VRL method implementations were not inducing statistically different results.

Although, we may have not been able to rank all our implemented VRL methods for each UCC metric, but it is important to recall that ranking methods wasn't the primary goal of our experiment. Instead, the primary goal was to assess the UCC framework as a tool for discussing VRL methods holistically in the context of sickness, presence, and fatigue; and as a tool for

providing potential insights to a better solution. The framework has demonstrated its usability in supporting the coherent discussion by allowing the implemented methods to be compared and differentiated.

Chapter 7 Conclusion

VRL is an interesting problem to study because it has been a consistent significant challenge.

While existing literature discusses the UCC metrics we have identified, it usually does not examine their relation to one another. We believe that future work in VRL should be focused on the trade-offs that exist between these three dimensions.

7.1 Contributions

The UCC framework can be a useful tool for VRL research. We have shown that it provides a common language for coherent discussion about the comparative strengths and weaknesses of different VRL methods. The UCC framework can describe the characteristics of the ideal VRL method, but it does not suggest how to achieve them.

It is likely that the perfect VRL solution will be very a long-term goal. In the short term the UCC framework can assist in finding specialized VRL solutions for specific application needs. Since VRL methods show signs of a trade-off between the UCC metrics, a VRL method can purposefully sacrifice performance in one UCC metric to improve performance in another metric that is deemed more important.

Finally, in building the testbed we provided useful insights into the challenges of eliciting the UCC metrics. Inducing too much sickness can jeopardize a user's well-being but inducing too little sickness won't adequately test the metric. It can be challenging to measure users' presence if they have not prior VR experience. Designing the test duration too short it won't cause fatigue, while too long hinder tester recruitment.

7.2 Future work

There are many opportunities for further research into VRL by building on the results of this study. A similar study could be conducted with more users, possibly controlling for prior VR experience and propensity for sickness. Similarly, this study could be repeated for a greater number of different VRL methods. Alternatively, the testbed can be improved to better elicit UCC metrics to better capture the methods. Through continued refinement a standardized testbed and set of appropriate questionnaires could be developed.

References

- [1] “Virtual reality | Define Virtual reality at Dictionary.com.” [Online]. Available: <http://www.dictionary.com/browse/virtual-reality>
- [2] C. Boletsis, “The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology,” *Multimodal Technol. Interact.*, vol. 1, no. 4, p. 24, Sep. 2017.
- [3] R. Bashara, “Solving VR’s Locomotion Problem,” *VR Fitness Insider*. 29-Nov-2017 [Online]. Available: <https://www.vrfitnessinsider.com/solving-vrs-locomotion-problem/>
- [4] “VR Locomotion Is A Problem That Has Many Half-Solutions,” *Tom’s Hardware*, 01-Dec-2016. [Online]. Available: <https://www.tomshardware.com/news/vr-locomotion-developer-solution-roundup,33108.html>
- [5] E. M. Kolasinski, “Simulator Sickness in Virtual Environments.,” ARMY RESEARCH INST FOR THE BEHAVIORAL AND SOCIAL SCIENCES ALEXANDRIA VA, ARMY RESEARCH INST FOR THE BEHAVIORAL AND SOCIAL SCIENCES ALEXANDRIA VA, ARI-TR-1027, May 1995 [Online]. Available: <http://www.dtic.mil/docs/citations/ADA295861>
- [6] S. V. G. Cobb, S. Nichols, A. Ramsey, and J. R. Wilson, “Virtual Reality-Induced Symptoms and Effects (VRISE),” *Presence Teleoperators Virtual Environ.*, vol. 8, no. 2, pp. 169–186, Apr. 1999.
- [7] J. T. Reason and J. J. Brand, *Motion sickness*. Oxford, England: Academic Press, 1975.
- [8] G. Welch and E. Foxlin, “Motion tracking: no silver bullet, but a respectable arsenal,” *IEEE Comput. Graph. Appl.*, vol. 22, no. 6, pp. 24–38, Nov. 2002.
- [9] “Comparison of virtual reality headsets,” *Wikipedia*. 14-Apr-2018 [Online]. Available: https://en.wikipedia.org/w/index.php?title=Comparison_of_virtual_reality_headsets&oldid=836390303#PC-based_devices
- [10] M. Nabyouni, A. Saktheeswaran, D. A. Bowman, and A. Karanth, “Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality,” in *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, 2015, pp. 3–10.
- [11] J. J. W. Lin, H. B. L. Duh, D. E. Parker, H. Abi-Rached, and T. A. Furness, “Effects of field of view on presence, enjoyment, memory, and simulator sickness in a virtual environment,” in *Proceedings IEEE Virtual Reality 2002*, 2002, pp. 164–171.
- [12] D. A. Bowman and R. P. McMahan, “Virtual Reality: How Much Immersion Is Enough?,” *Computer*, vol. 40, no. 7, pp. 36–43, Jul. 2007.
- [13] M. Slater and S. Wilbur, “A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments,” *Presence Teleoperators Virtual Environ.*, vol. 6, no. 6, pp. 603–616, Dec. 1997.
- [14] C. Heeter, “Being There: The Subjective Experience of Presence,” *Presence Teleoperators Virtual Environ.*, vol. 1, no. 2, pp. 262–271, Jan. 1992.
- [15] M. J. Schuemie, P. van der Straaten, M. Krijn, and C. A. P. G. van der Mast, “Research on Presence in Virtual Reality: A Survey,” *Cyberpsychol. Behav.*, vol. 4, no. 2, pp. 183–201, Apr. 2001.
- [16] J. Bhandari, S. Tregillus, and eelke folmer, *Legomotion: Scalable Walking-based Locomotion* *. 2017.
- [17] G. Llorach, A. Evans, and J. Blat, “Simulator Sickness and Presence using HMDs: comparing use of a game controller and a position estimation system,” p. 4.

- [18] S. Nichols, "Physical ergonomics of virtual environment use," *Appl. Ergon.*, vol. 30, no. 1, pp. 79–90, Feb. 1999.
- [19] M. Bachynskyi, "Biomechanical models for human-computer interaction," 2016.
- [20] "Kinect," *Wikipedia*. 12-May-2018 [Online]. Available: <https://en.wikipedia.org/w/index.php?title=Kinect&oldid=840783136>
- [21] Y. Kim, G. A. Lee, D. Jo, U. Yang, G. Kim, and J. Park, "Analysis on virtual interaction-induced fatigue and difficulty in manipulation for interactive 3D gaming console," in *2011 IEEE International Conference on Consumer Electronics (ICCE)*, 2011, pp. 269–270.
- [22] J. Lee, M. Kim, and J. Kim, "A Study on Immersion and VR Sickness in Walking Interaction for Immersive Virtual Reality Applications," *Symmetry*, vol. 9, no. 5, p. 78, May 2017.
- [23] J. Frommel, S. Sonntag, and M. Weber, "Effects of Controller-based Locomotion on Player Experience in a Virtual Reality Exploration Game," in *Proceedings of the 12th International Conference on the Foundations of Digital Games*, New York, NY, USA, 2017, pp. 30:1–30:6 [Online]. Available: <http://doi.acm.org/10.1145/3102071.3102082>
- [24] D. A. Bowman, D. Koller, and L. F. Hodges, "Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques," 1997, pp. 45-52, [Online]. Available: <http://ieeexplore.ieee.org/document/583043/>
- [25] L. L. Arns, "A new taxonomy for locomotion in virtual environments," p. 227.
- [26] O. Merhi, E. Faugloire, M. Flanagan, and T. A. Stoffregen, "Motion Sickness, Console Video Games, and Head-Mounted Displays," *Hum. Factors*, vol. 49, no. 5, pp. 920–934, Oct. 2007.
- [27] E. Bozgeyikli, A. Raji, S. Katkooi, and R. Dubey, "Point & Teleport Locomotion Technique for Virtual Reality," in *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play*, New York, NY, USA, 2016, pp. 205–216 [Online]. Available: <http://doi.acm.org/10.1145/2967934.2968105>
- [28] M. Usoh *et al.*, "Walking >> Walking-in-place >> Flying, in Virtual Environments," in *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, New York, NY, USA, 1999, pp. 359–364 [Online]. Available: <http://dx.doi.org/10.1145/311535.311589>
- [29] A. Kitson, A. M. Hashemian, E. R. Stepanova, E. Kruijff, and B. E. Riecke, "Comparing leaning-based motion cueing interfaces for virtual reality locomotion," in *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, 2017, pp. 73–82.
- [30] D. A. Bowman, D. Koller, and L. F. Hodges, "A methodology for the evaluation of travel techniques for immersive virtual environments," *Virtual Real.*, vol. 3, no. 2, pp. 120–131, Jun. 1998.
- [31] "Welcome to VRTK · VRTK - Virtual Reality Toolkit," *VRTK - Virtual Reality Toolkit*. [Online]. Available: <https://vrtoolkit.readme.io/docs>
- [32] S. M. Ebenholtz, "Motion Sickness and Oculomotor Systems in Virtual Environments," *Presence Teleoperators Virtual Environ.*, vol. 1, no. 3, pp. 302–305, Jan. 1992.
- [33] T. M. Porcino, E. Clua, D. Trevisan, C. N. Vasconcelos, and L. Valente, "Minimizing cyber sickness in head mounted display systems: Design guidelines and applications," in *2017 IEEE 5th International Conference on Serious Games and Applications for Health (SeGAH)*, 2017, pp. 1–6.
- [34] "About the VIVE controllers." [Online]. Available: https://www.vive.com/us/support/vive/category_howto/about-the-controllers.html

- [35] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *Int. J. Aviat. Psychol.*, vol. 3, no. 3, pp. 203–220, Jul. 1993.
- [36] "igroup presence questionnaire (IPQ) overview | igroup.org – project consortium." [Online]. Available: <http://www.igroup.org/pq/ipq/index.php>
- [37] T. Schubert, F. Friedmann, and H. Regenbrecht, "The Experience of Presence: Factor Analytic Insights," *Presence Teleoperators Virtual Environ.*, vol. 10, no. 3, pp. 266–281, Jun. 2001.
- [38] B. G. Witmer and M. J. Singer, "Measuring Presence in Virtual Environments: A Presence Questionnaire," *Presence Teleoperators Virtual Environ.*, vol. 7, no. 3, pp. 225–240, Jun. 1998.
- [39] A. Assila and K. Marçal, "Standardized Usability Questionnaires: Features and Quality Focus," vol. 6, no. 1, p. 17, 2016.
- [40] G. Borg, "Psychophysical scaling with applications in physical work and the perception of exertion," *Scand. J. Work. Environ. Health*, vol. 16, pp. 55–58, 1990.
- [41] "Load the Analysis ToolPak in Excel." [Online]. Available: <https://support.office.com/en-us/article/load-the-analysis-toolpak-in-excel-6a63e598-cd6d-42e3-9317-6b40ba1a66b4>
- [42] "Performing Real Statistical Analysis Using Excel." [Online]. Available: <http://www.real-statistics.com/>
- [43] "Likert scale," *Wikipedia*. 31-May-2018 [Online]. Available: https://en.wikipedia.org/w/index.php?title=Likert_scale&oldid=843784282

Appendix A: Assets Used

Hardware

HTC Vive: 90 Hz refresh rate, 110-degree field of view, resolution of 1080x1200 pixels per eye

Dell Inspiron 7577 laptop: 6GB NVidia GTX 1060a, 2.5 GHz processor, 8 GB DDR4 RAM

Software

Unity 2017

<https://unity3d.com/>

VRTK - Virtual Reality Toolkit - [VR Toolkit] by Sysdia Solutions Ltd

<https://assetstore.unity.com/packages/tools/vrtoolkit-vr-toolkit-64131>

Low-Poly Park by Thunderent's Assets

<https://assetstore.unity.com/packages/3d/environments/urban/low-poly-park-61922>

Low Poly Sci Fi Set by Walter Palladino

<https://assetstore.unity.com/packages/3d/environments/sci-fi/low-poly-sci-fi-set-110775>

LowPoly Environment Pack by Korveen

<https://assetstore.unity.com/packages/3d/environments/landscapes/lowpoly-environment-pack-99479>

Lowpoly Wooden Chest by Frut

<https://assetstore.unity.com/packages/3d/props/lowpoly-wooden-chest-93960>

Handpainted Keys by RoboCG

<https://assetstore.unity.com/packages/3d/handpainted-keys-42044>

Stylized Crystal by LowlyPoly

<https://assetstore.unity.com/packages/3d/props/stylized-crystal-77275>

Sound Effects and Ambient Noise

<https://freesound.org/>

Appendix B: Questions Asked

Demographics

Describe your virtual reality experience	None-Minor-Moderate-Extensive
Describe your video game experience	None-Minor-Moderate-Extensive
Describe how often you get motion sickness	Never-Rarely-Frequently-Always
What is your age?	#

Sickness

Did you feel nauseous?	No-Slightly-Moderately-Severe
Did you get indigestion or burp?	No-Slightly-Moderately-Severe
Did you feel dizzy?	No-Slightly-Moderately-Severe
Did you get a headache?	No-Slightly-Moderately-Severe

Presence

Did you feel you were actually in the virtual space?	No-Slightly-Moderately-Extremely
Did you lose awareness of the real world?	No-Slightly-Moderately-Extremely
Did you get a sense of the distance & scale?	No-Slightly-Moderately-Extremely
Did you get a sense spatial relation & orientation?	No-Slightly-Moderately-Extremely

Fatigue

Did you feel it was hard to move around the virtual space?	No-Slightly-Moderately-Extremely
Did you find the navigation mentally demanding?	No-Slightly-Moderately-Extremely
Did you find the navigation physically strenuous?	No-Slightly-Moderately-Extremely
Do you think continued use would leave you exhausted?	No-Slightly-Moderately-Extremely

Comparison

Rank which made you the sickest	Walking-Controller-Teleport
Rank which made you the most immersed	Walking-Controller-Teleport
Rank which made you the most tired	Walking-Controller-Teleport
Rank which was most like “Virtual Reality”	Walking-Controller-Teleport
Rank which you prefer to use	Walking-Controller-Teleport

Appendix C: Data Collected

Timestamp	Order	Age	Describe How Often You Get Motion Sickness	Describe Your Virtual Reality Experience	Describe Your Video Game Experience	Method Selected	Method 1 Time	Sickness [Did you feel nauseous?]	Sickness [Did you get indigestion or burp?]	Sickness [Did you feel dizzy?]	Sickness [Did you get a headache?]	Sickness [Sum]	Presence [Did you feel you were actually in the virtual space?]	Presence [Did you lose awareness of the real world?]	Presence [Did you get a sense of the distance & scale?]	Presence [Did you get a sense spatial relation & orientation?]	Presence [Sum]	Fatigue [Did you feel it was hard to move around the virtual space?]	Fatigue [Did you find the navigation mentally demanding?]	Fatigue [Did you find the navigation physically strenuous?]	Fatigue [Do you think that continued use would leave you exhausted?]	Fatigue [Sum]
4/10/2018 14:36:37	Walking/Controller/Teleport	50	2	1	4	Walking	349	1	1	2	1	5	3	3	3	3	12	1	1	1	1	4
4/10/2018 15:07:12	Teleport/Controller/Walking	34	2	1	4	Teleport	217	1	1	1	1	4	3	3	3	2	11	1	1	1	1	4
4/10/2018 16:07:52	Controller/Walking/Teleport	17	1	1	4	Controller	453	1	1	1	1	4	4	3	3	4	14	2	1	1	1	5
4/10/2018 16:37:33	Teleport/Walking/Controller	20	1	1	4	Teleport	403	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
4/10/2018 17:04:46	Controller/Walking/Teleport	16	1	1	4	Controller	401	1	1	1	1	4	3	3	4	4	14	2	1	1	1	6
4/10/2018 17:36:31	Walking/Teleport/Controller	19	2	1	4	Walking	467	1	1	2	1	5	4	4	4	4	16	2	1	2	2	7
4/10/2018 19:11:10	Teleport/Controller/Walking	28	2	1	4	Teleport	265	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
4/10/2018 19:32:08	Walking/Controller/Teleport	28	2	1	4	Walking	173	1	1	3	1	6	3	3	4	4	14	2	1	2	3	8
4/10/2018 20:11:25	Controller/Teleport/Walking	39	1	1	2	Controller	581	1	1	2	1	5	4	3	4	3	14	2	2	1	1	6
4/10/2018 22:10:21	Teleport/Walking/Controller	40	1	1	3	Teleport	347	1	1	2	1	5	4	4	4	4	16	1	1	1	1	4
4/12/2018 14:49:28	Walking/Teleport/Controller	31	2	1	2	Walking	443	1	1	1	1	4	3	4	3	4	14	2	2	1	2	7
4/12/2018 16:08:06	Controller/Walking/Teleport	23	3	2	4	Controller	486	1	1	1	1	4	4	3	4	3	14	3	2	1	2	8
4/12/2018 18:00:24	Walking/Controller/Teleport	23	1	3	1	Walking	753	1	1	1	1	4	4	4	2	3	13	3	2	1	2	8
4/18/2018 16:10:45	Controller/Teleport/Walking	24	2	2	3	Controller	445	2	1	3	1	7	3	3	4	3	13	2	2	1	3	8
4/18/2018 16:54:59	Walking/Teleport/Controller	27	1	2	1	Walking	457	1	1	2	1	5	4	2	3	3	12	2	1	2	3	8
4/18/2018 17:31:27	Teleport/Controller/Walking	29	1	2	3	Teleport	316	1	1	1	1	4	4	3	4	3	14	1	1	1	2	5
4/25/2018 15:57:41	Teleport/Walking/Controller	49	3	1	2	Teleport	564	3	3	2	1	9	3	2	4	3	12	2	2	1	3	8
4/28/2018 17:06:06	Controller/Teleport/Walking	35	1	2	4	Controller	302	1	1	1	1	4	4	4	3	4	15	1	1	1	2	5
4/28/2018 17:39:00	Teleport/Walking/Controller	8	2	1	3	Teleport	282	1	1	1	1	4	4	3	2	3	12	2	2	1	1	6
4/28/2018 18:12:17	Controller/Walking/Teleport	15	1	2	4	Controller	363	1	1	1	1	4	3	4	4	4	15	1	1	1	2	5
4/28/2018 18:41:44	Teleport/Controller/Walking	31	2	1	2	Teleport	280	1	1	2	1	5	4	3	3	3	13	1	2	1	1	5
4/28/2018 19:24:26	Walking/Teleport/Controller	48	1	1	3	Walking	418	1	1	1	1	4	3	4	4	4	15	1	1	1	1	4
4/28/2018 20:13:07	Walking/Controller/Teleport	48	2	1	3	Walking	654	1	1	2	1	5	4	4	4	4	16	2	2	3	4	11
4/28/2018 20:56:17	Controller/Teleport/Walking	32	2	1	3	Controller	338	2	1	2	1	6	3	2	4	4	13	1	1	1	2	5
4/30/2018 13:36:06	Controller/Teleport/Walking	21	1	2	3	Controller	238	1	1	1	1	4	3	3	3	3	12	1	1	1	1	4
4/30/2018 14:46:45	Teleport/Walking/Controller	44	2	1	2	Teleport	331	2	1	2	1	6	3	3	4	3	13	1	1	1	2	5
4/30/2018 15:28:38	Walking/Controller/Teleport	21	3	1	3	Walking	280	3	1	2	2	8	4	4	4	4	16	1	1	1	3	6
4/30/2018 16:12:36	Controller/Walking/Teleport	27	2	2	3	Controller	282	1	1	2	1	5	4	4	4	4	16	3	2	1	3	9
4/30/2018 16:47:08	Walking/Teleport/Controller	22	2	1	2	Walking	350	1	1	3	2	7	4	3	4	4	15	2	2	1	2	7
4/30/2018 17:51:41	Teleport/Controller/Walking	21	2	2	3	Teleport	126	1	1	1	1	4	3	2	3	4	12	1	1	1	2	5

Method Selected	Method 2 Time	Sickness [Did you feel nauseous?]	Sickness [Did you get indigestion or burp?]	Sickness [Did you feel dizzy?]	Sickness [Did you get a headache?]	Sickness [Sum]	Presence [Did you feel you were actually in the virtual space?]	Presence [Did you lose awareness of the real world?]	Presence [Did you get a sense of the distance & scale?]	Presence [Did you get a sense spatial relation & orientation?]	Presence [Sum]	Fatigue [Did you feel it was hard to move around the virtual space?]	Fatigue [Did you find the navigation mentally demanding?]	Fatigue [Did you find the navigation physically strenuous?]	Fatigue [Do you think that continued use would leave you exhausted?]	Fatigue [Sum]
Controller	237	1	1	2	1	5	3	3	3	3	12	1	1	1	1	4
Controller	184	2	1	2	1	6	3	3	3	3	12	1	1	1	1	4
Walking	167	1	1	1	1	4	3	3	4	4	14	1	1	2	4	8
Walking	349	1	1	1	1	4	4	4	4	4	16	1	1	2	3	7
Walking	311	1	1	1	1	4	4	3	4	4	15	1	1	1	2	5
Teleport	299	1	1	1	1	4	4	4	4	4	16	1	1	1	2	5
Controller	188	4	1	4	1	10	4	4	4	4	16	3	4	2	3	12
Controller	231	2	1	3	2	8	2	2	3	4	11	2	4	1	3	10
Teleport	277	1	1	1	1	4	4	4	4	1	13	1	1	1	2	5
Walking	347	1	1	2	1	5	4	4	4	4	16	1	1	1	1	4
Teleport	312	1	1	1	1	4	4	4	4	4	16	1	2	1	2	6
Walking	306	1	1	1	1	4	4	3	4	4	15	2	1	2	4	9
Controller	605	1	1	1	1	4	3	2	1	1	7	3	2	1	1	7
Teleport	189	2	1	2	1	6	3	3	3	3	12	2	3	3	4	12
Teleport	209	1	1	1	1	4	3	2	3	2	10	1	1	1	2	5
Controller	156	2	1	2	1	6	4	4	3	4	15	2	1	1	2	6
Walking	354	4	3	4	2	13	4	4	4	4	16	2	3	3	4	12
Teleport	176	1	1	1	1	4	3	3	2	3	11	1	2	1	2	6
Walking	378	1	1	1	1	4	4	4	4	4	16	4	1	2	2	9
Walking	292	1	1	1	1	4	4	4	4	4	16	1	1	2	3	7
Controller	199	3	1	3	1	8	3	3	3	3	12	1	2	1	2	6
Teleport	104	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
Controller	301	3	1	3	1	8	4	4	4	4	16	2	3	3	4	12
Teleport	243	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
Teleport	158	1	1	1	1	4	3	2	2	2	9	2	2	1	1	6
Walking	445	3	1	2	1	7	3	4	4	3	14	3	3	4	4	14
Controller	125	3	1	2	2	8	2	3	4	4	13	3	1	1	3	8
Walking	111	1	1	2	1	5	4	4	4	4	16	2	1	2	4	9
Teleport	377	1	1	1	1	4	2	3	4	4	13	1	1	1	1	4
Controller	128	1	1	1	1	4	3	2	3	4	12	1	1	1	1	4
Teleport	270	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
Walking	107	2	1	2	2	7	3	3	3	3	12	1	1	1	1	4
Teleport	121	1	1	1	1	4	4	4	3	3	14	1	1	1	1	4
Controller	259	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
Teleport	257	1	1	1	1	4	4	3	3	3	13	2	2	1	1	6
Controller	277	1	1	1	1	4	3	4	4	3	14	3	1	1	2	7
Walking	334	2	1	2	1	6	4	4	4	4	16	2	1	3	4	10
Teleport	146	1	1	1	1	4	3	3	2	3	11	2	1	1	2	6
Walking	240	1	1	2	1	5	4	4	4	4	16	2	2	2	3	9
Controller	354	1	1	2	1	5	4	4	4	4	16	1	1	1	1	4
Controller	297	2	1	2	1	6	4	4	4	4	16	2	3	1	2	8
Teleport	464	1	1	2	1	5	4	4	4	4	16	1	1	1	1	4
Teleport	353	1	1	1	1	4	2	2	2	3	9	1	1	1	1	4
Walking	272	2	1	2	1	6	4	4	3	3	14	2	2	2	3	9
Controller	200	1	1	4	1	7	3	2	4	3	12	1	1	1	4	7
Walking	189	1	1	1	1	4	3	3	3	3	12	2	2	4	4	12
Controller	411	3	3	3	1	10	4	3	4	4	15	2	3	3	4	12
Walking	168	1	1	1	1	4	4	4	4	4	16	1	1	3	4	9
Controller	246	1	1	1	1	4	4	4	3	4	14	1	1	1	1	4
Teleport	348	1	1	1	1	4	3	3	4	4	14	1	1	1	1	4
Walking	162	2	1	2	1	6	4	4	4	4	16	3	3	3	4	13
Controller	219	2	1	2	1	6	4	4	4	4	16	2	2	1	1	6
Teleport	172	1	1	1	1	4	4	4	4	4	16	1	1	1	1	4
Walking	228	3	1	1	1	6	4	4	4	4	16	1	1	3	4	9
Walking	169	1	1	2	1	5	4	3	3	4	14	2	2	3	3	10
Controller	359	2	1	2	1	6	3	3	2	3	11	3	3	2	2	10
Teleport	196	2	1	2	2	7	2	3	3	2	10	4	2	1	2	9
Teleport	101	1	1	1	1	4	2	4	3	2	11	2	1	1	1	5
Controller	211	1	1	1	1	4	2	3	4	4	13	2	1	1	1	5
Walking	238	1	1	1	1	4	4	4	3	4	15	3	2	2	3	10

